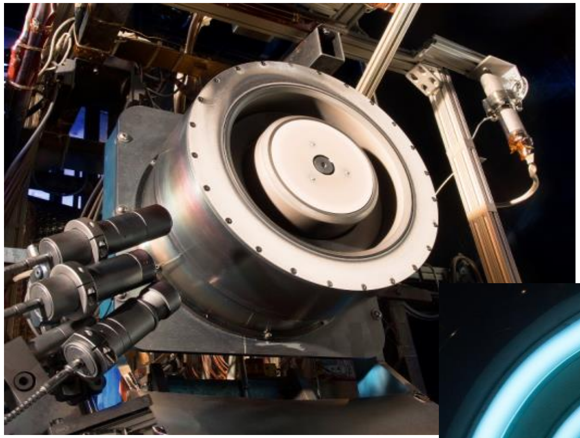
Development of High Power Hall Thruster Systems to Enable the NASA Exploration Vision



Jerry Jackson, Joseph Cassady, May Allen and Roger Myers
Aerojet Rocketdyne, Los Angeles, CA and Redmond, WA

And

Todd Tofil, Dan Herman and Eric Pencil
NASA Glenn Research Center, Cleveland, Ohio, 44135

Space Propulsion 2018
Sponsored by 3AF
Barcelo Renacimiento Hotel Convention Center •
Seville • Spain
May 14-18, 2018

OUTLINE

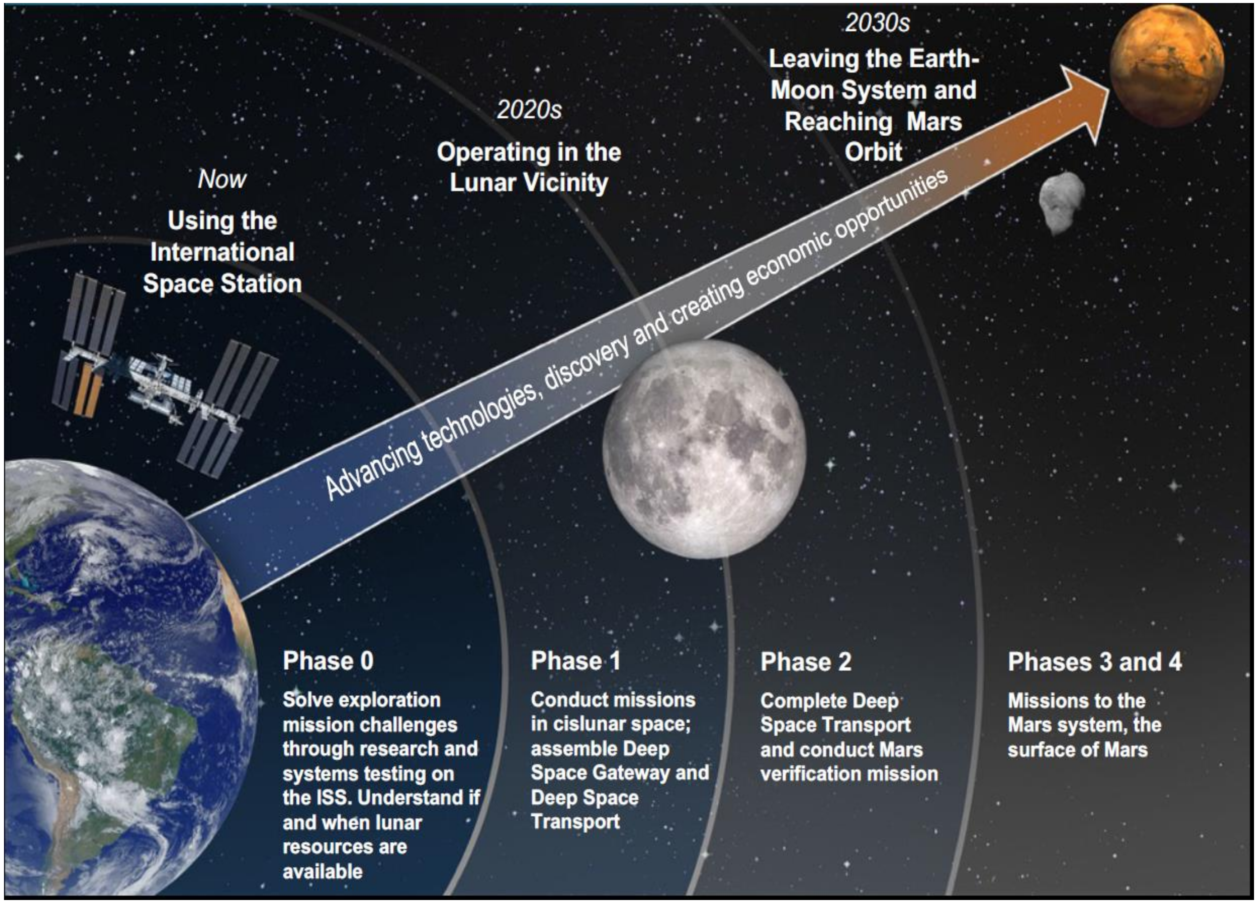
- NASA Vision for Deep Space Exploration
- Advanced Electric Propulsion System (AEPS) Program Summary
  - Program Information
  - Status
- AEPS Component Overviews
  - Thruster , PPU, XFC
- AEPS Summary

- NextSTEP
  - Program Information
  - Status
- NextSTEP Component Overviews
  - Thruster, PPU, Feed System
- NextSTEP Summary

NASA Vision for Deep Space Exploration

High power solar electric propulsion (SEP) systems are:

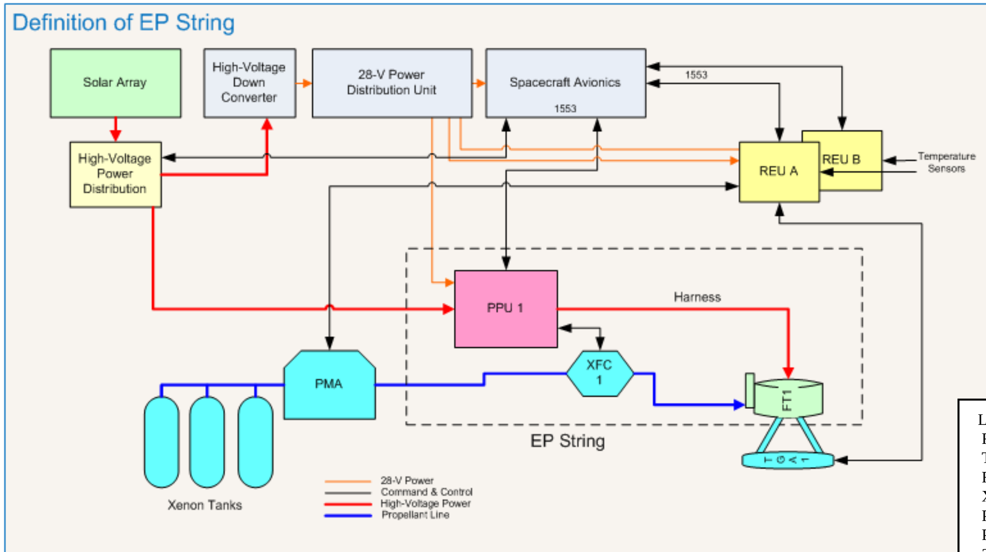
- Integral to NASA's phased exploration vision
- An enabling technology for future science missions



Future SEP systems should have the flexibility to accommodate a range of missions.

Present NASA programs support the short and long term vision for exploration.

AEPS PROGRAM SUMMARY



Legend:
REU: Remote Engineering Unit
TGA: Thruster Gimbal Assembly
FT: Flight Thruster
XFC: Xenon Flow Controller
PPU: Power Processing Unit
PMA: Propellant Management Assembly
28V: Low Voltage Bus

PROGRAM ELEMENTS

Base Period

Period of Performance: 05/16/2016 – 01/23/2019

Scope: Develop the PPU, Hall Current Thruster & Xenon Flow Controller; Perform system test of EDU EP String

Option Period

Period of Performance: 11/25/2018 – 05/20/2020 [tentative]

Scope: Qualify the AEPS flight EP string, deliver 5 Flight EP strings (incl. qualification EP string)

AEPS Goal is to Develop a 12.5 kW Hall Thruster EP System

Key Requirements and Capabilities

Requirement/Capability	Value
Propellant	Xenon
Input Power	3.0 to 14.0 kW
Input Voltage	95 to 140 V
HT Non-operating Temp	> -100C
PPU Non-Operating Temp	-45C to 80C
PPU Operating Temp	-15C to 50C
Throughput, kg	1770
Cycle Life, on/off	1700
Operational life	23,000 Hours

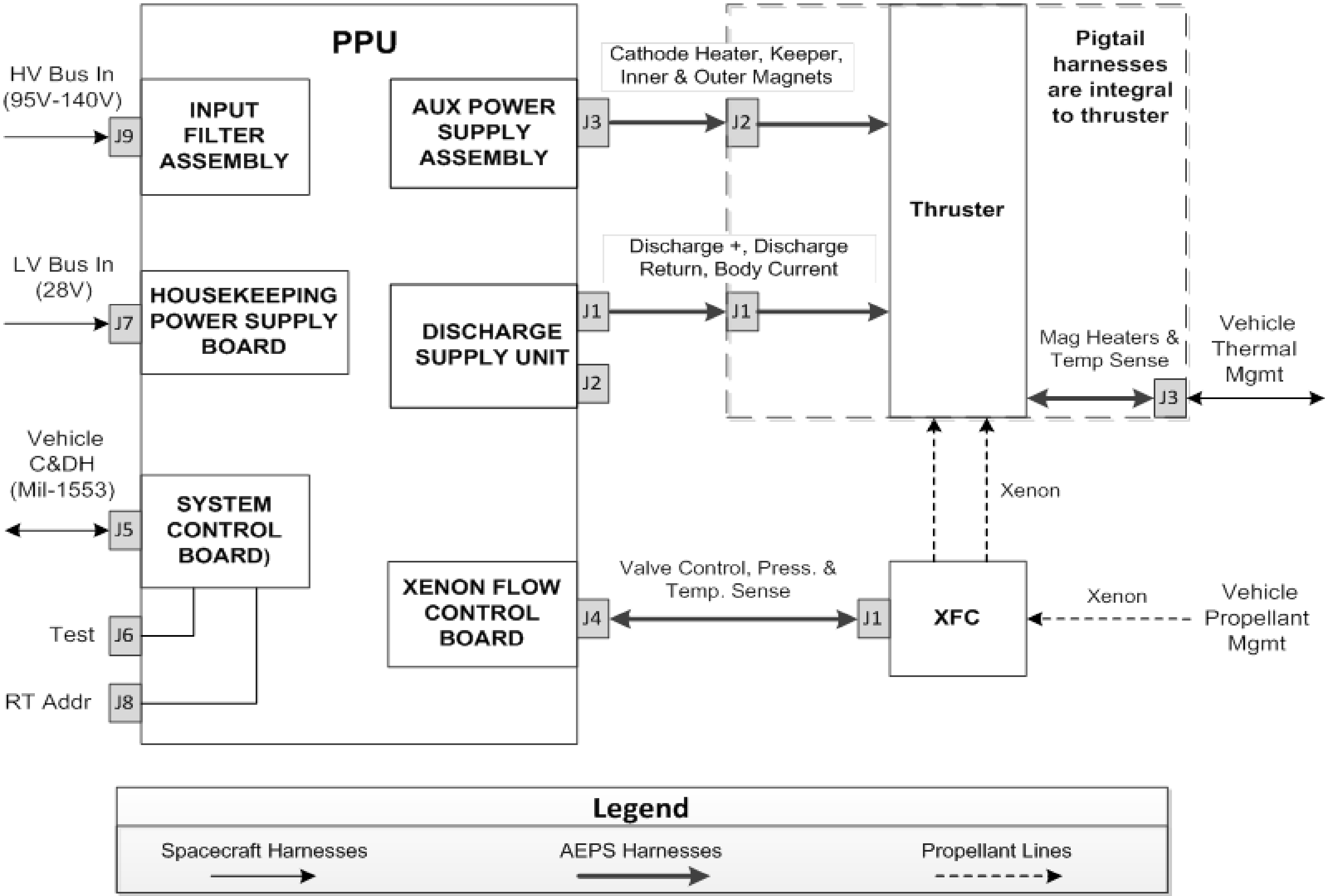
Meets needs of PPE for LOP

Concept for Lunar Orbiting Platform

Flexibility in Power and Discharge Voltage provide for a robust design

EP String Total Input Power	Discharge Voltage	Thrust	Specific Impulse	Total System Efficiency
13.3 kW	600 V	589 mN	2800 s	57%
11.1 kW	500 V	519 mN	2600 s	55%
8.9 kW	400 V	462 mN	2300 s	54%
6.7 kW	300 V	386 mN	1900 s	52%

AEPS System Block Diagram



System harnessing designed to support ease of spacecraft integration, including in-situ continuity testing

PROGRAM STATUS

- Completed System Requirements Review on Dec. 1st, 2016
- Completed System Test demo of PPU architecture in June 2017
- Completed PDR on Aug. 3rd, 2017
- Completed Software PDR in March 2018
- Completed re-design of PPU DSU to meet efficiency requirements

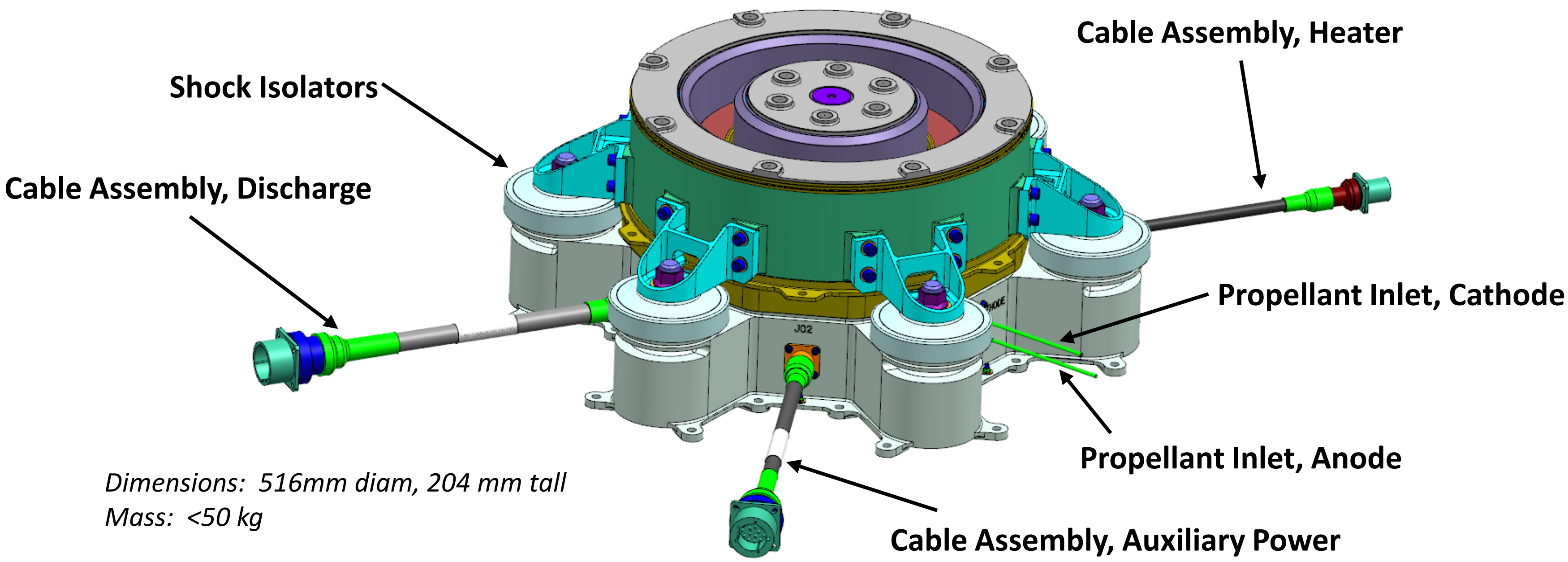
---

- Final EDU fidelity product definition in work
- XFC CDR planned for Oct., 2018
- EDU Component Fab & Assy planned for July 2018
- EDU Component Testing planned for Nov. 2018
- EDU System Test planned for Feb. 2019

AEPS Program Making Good Progress Toward 2019 Flight Qualification

AEPS Thruster

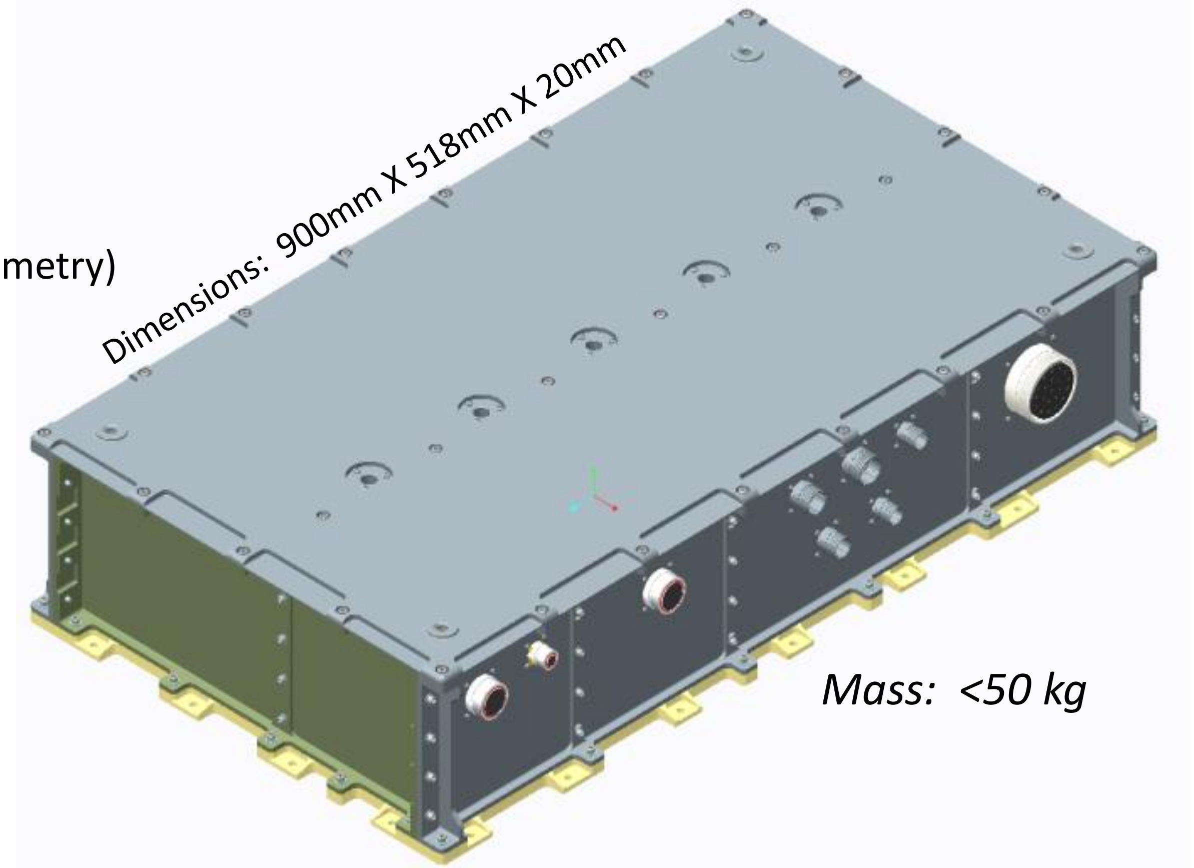
- Operating range: up to 25 A and 630 V discharge power
- Performance objectives: 68% efficiency, 600 mN and 2900 seconds Isp
- Launch environment: shock up to 1000 g, vibration up to 11.4 g_{rms}
- Operating environment: deep space anywhere between 0.8 AU and 1.7 AU while mounted to a spacecraft interface between -100°C and +150°C.
- With thermal conduction set to 0W, thruster radiates only 22 W to spacecraft
- Life: Designed for 23,000 hours of operation, over 5,000 starts and 15 year missions.



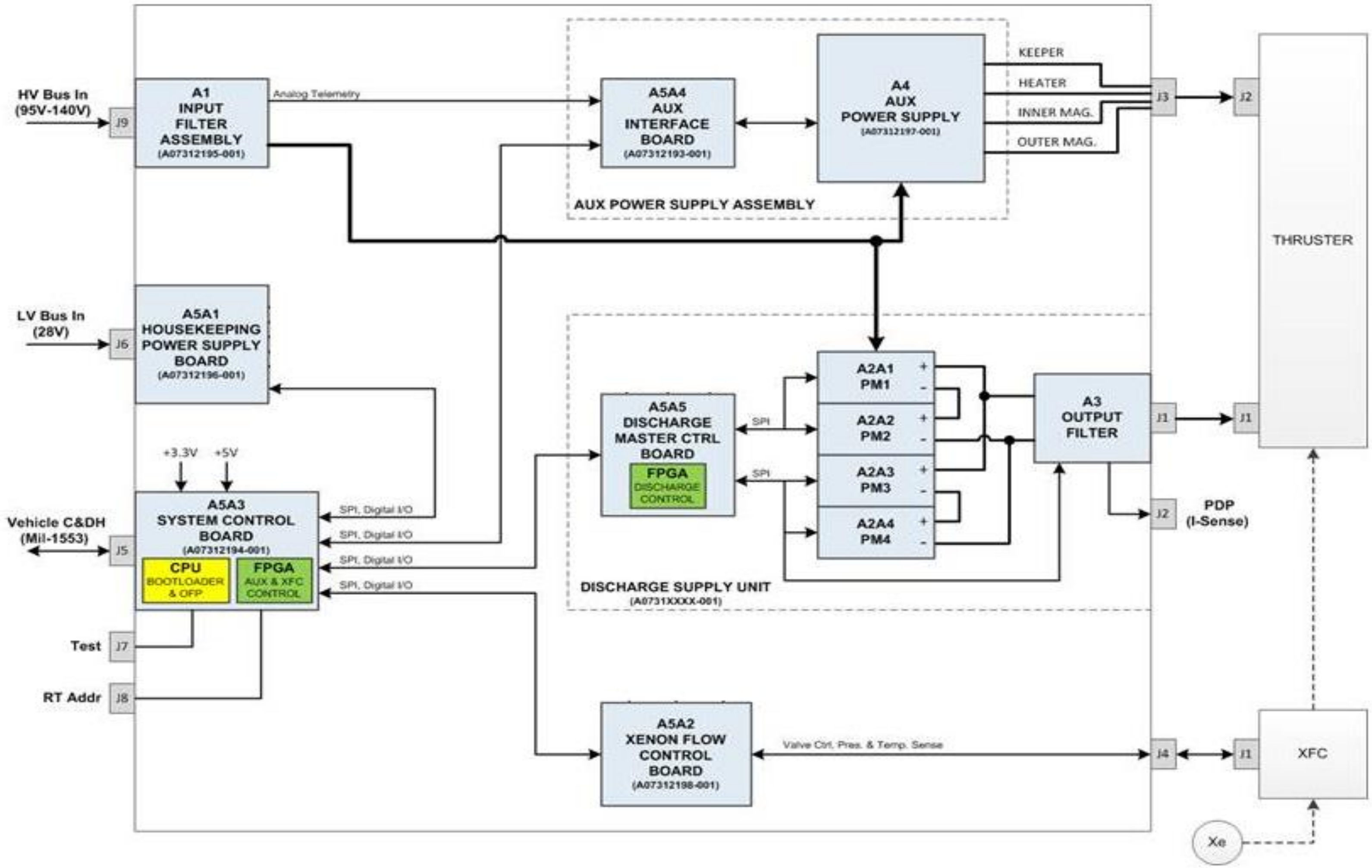
Dimensions: 516mm diam, 204 mm tall
Mass: <50 kg

AEPS Power Processing Unit

- Input Power: 13.3kW input (14kW contingency)
- Input voltage: 95V – 140V, Unregulated
- Output Voltage: 300V to 600V, 20.8A
- Output Power: 12.5kW at 600V
- Target Efficiency: 95%
- Provides:
  - XFC & Thruster Control
  - Command & Data Handling (Telemetry)
  - Fault Management

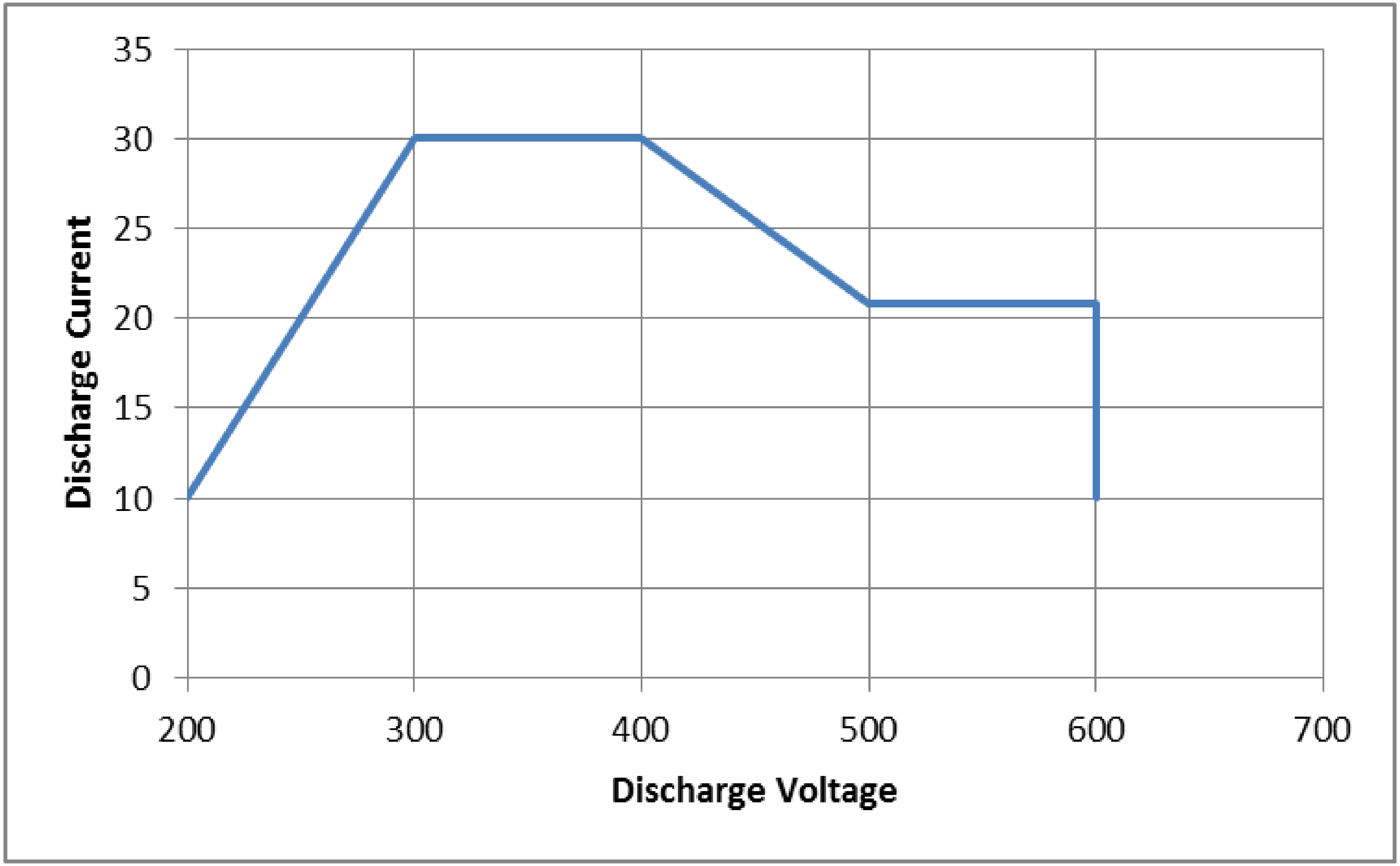


AEPS PPU Block Diagram



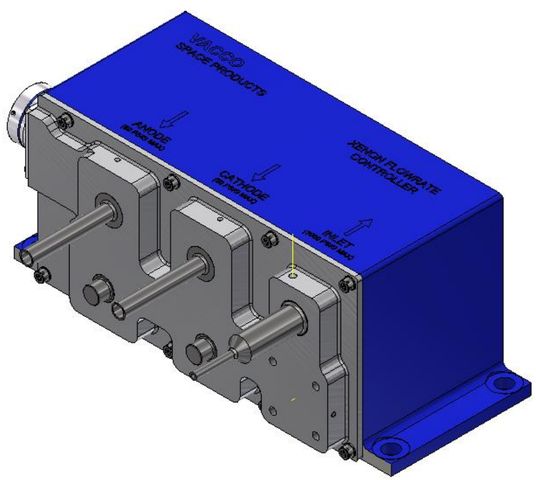
PPU Current Vs. Discharge Voltage

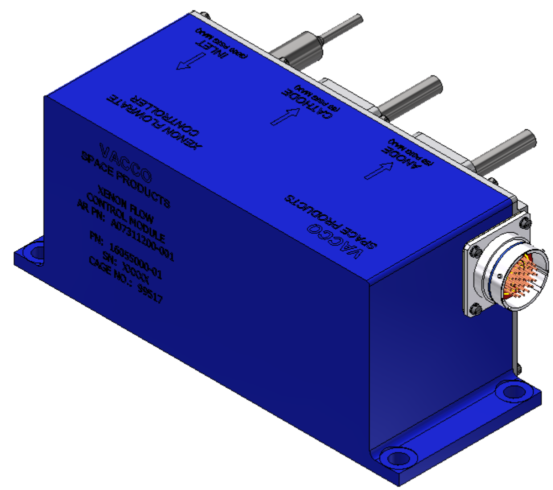
- PPU Design supports High Current Capability between 300-400V



AEPS XENON FLOW CONTROLLER (XFC)

- VACCO developed the XFC, a version of their fully-qualified XFCM, based on their Chemically Etched Micro-Systems (ChEMS™) Technology.
- XFC is a highly-integrated, compact, low-mass subsystem
- Designed for nominal inlet pressures regulated to 40 psia.
  - Will successfully operate at off-nominal inlet pressures up to 3,000 psia.
- Provides flow rate of 8 to 23 mg/second of xenon
- Provide a flow rate measurement accuracy of ± 1.25% at the inlet pressure of 40 psia and over a temperature range of 20°C to 50°C.
- Calibration testing is planned for June of 2018



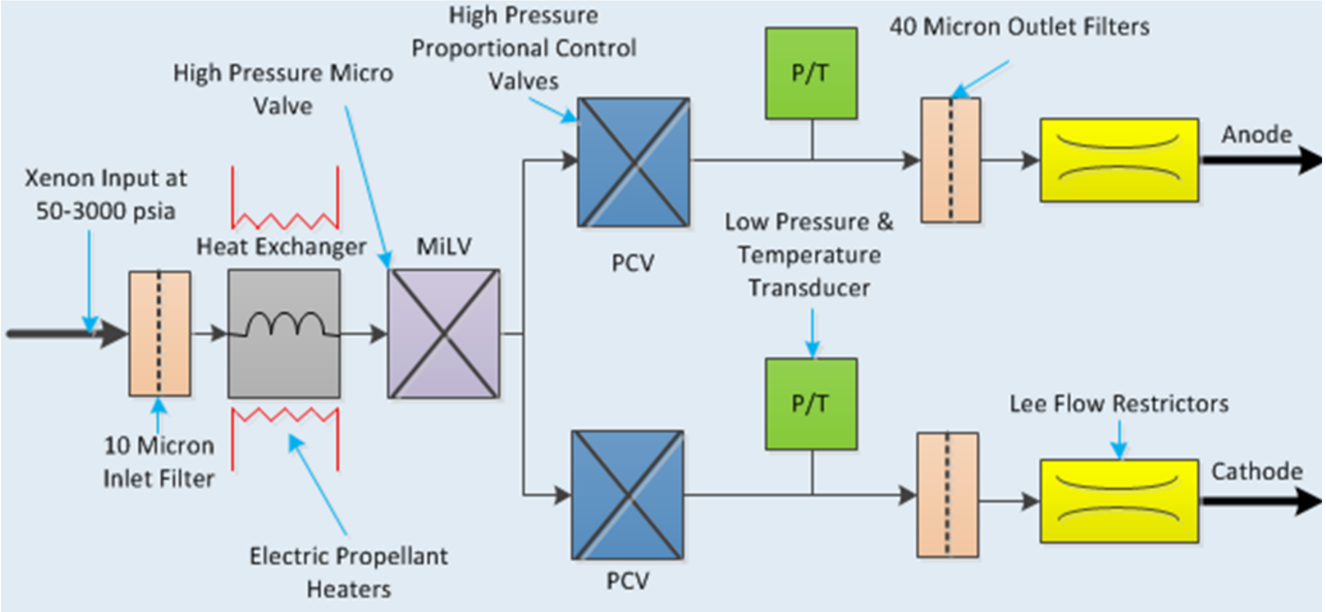


Mass: <2 kg

Dimensions: 80 x 80 x 200 mm

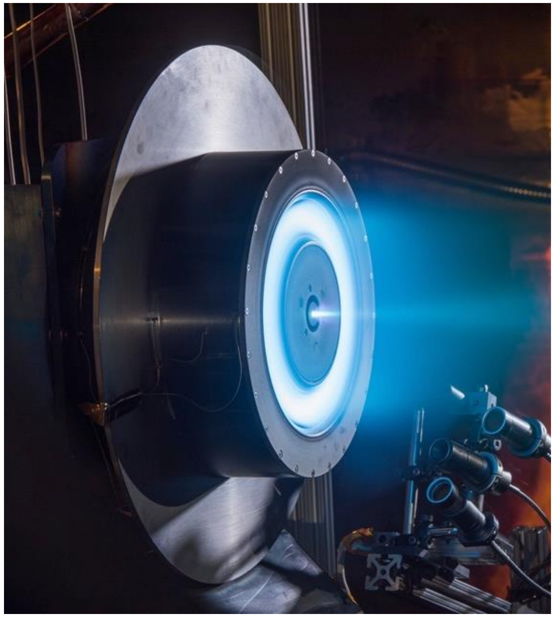
XFC Block Diagram

- 10 Micron propellant filtration of up to 1770 kg throughput
- Propellant heater for off-nominal conditions
- Micro Latch Valve for propellant isolation
- Independently throttleable flow to both the Anode and Cathode



AEPS Summary

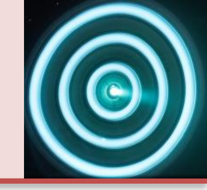
- AEPS System is a key SEP element to enable the vision of exploration
- AEPS Design provides for increased flexibility with
  - Incorporation of Elements typically found in Spacecraft Control of PPU
  - PPU which provides closed loop control of thruster and XFC
  - Modular design allowing for enhanced reliability



- Development progress is on track for delivery of EP systems to support Lunar Operating Platform –Gateway; the 1st step in permanent presence of human's beyond LEO
- Successful demonstration of AEPS approach via prototype System Test at NASA GRC
- Completed Successful PDR, on path to CDR in Winter of '18
- On target to support late 2019 completion of qualification test

AEPS is an enabling technology for large-scale NASA & Commercial Missions

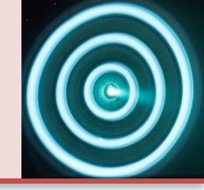
NEXTSTEP ADVANCED PROPULSION SYSTEMS



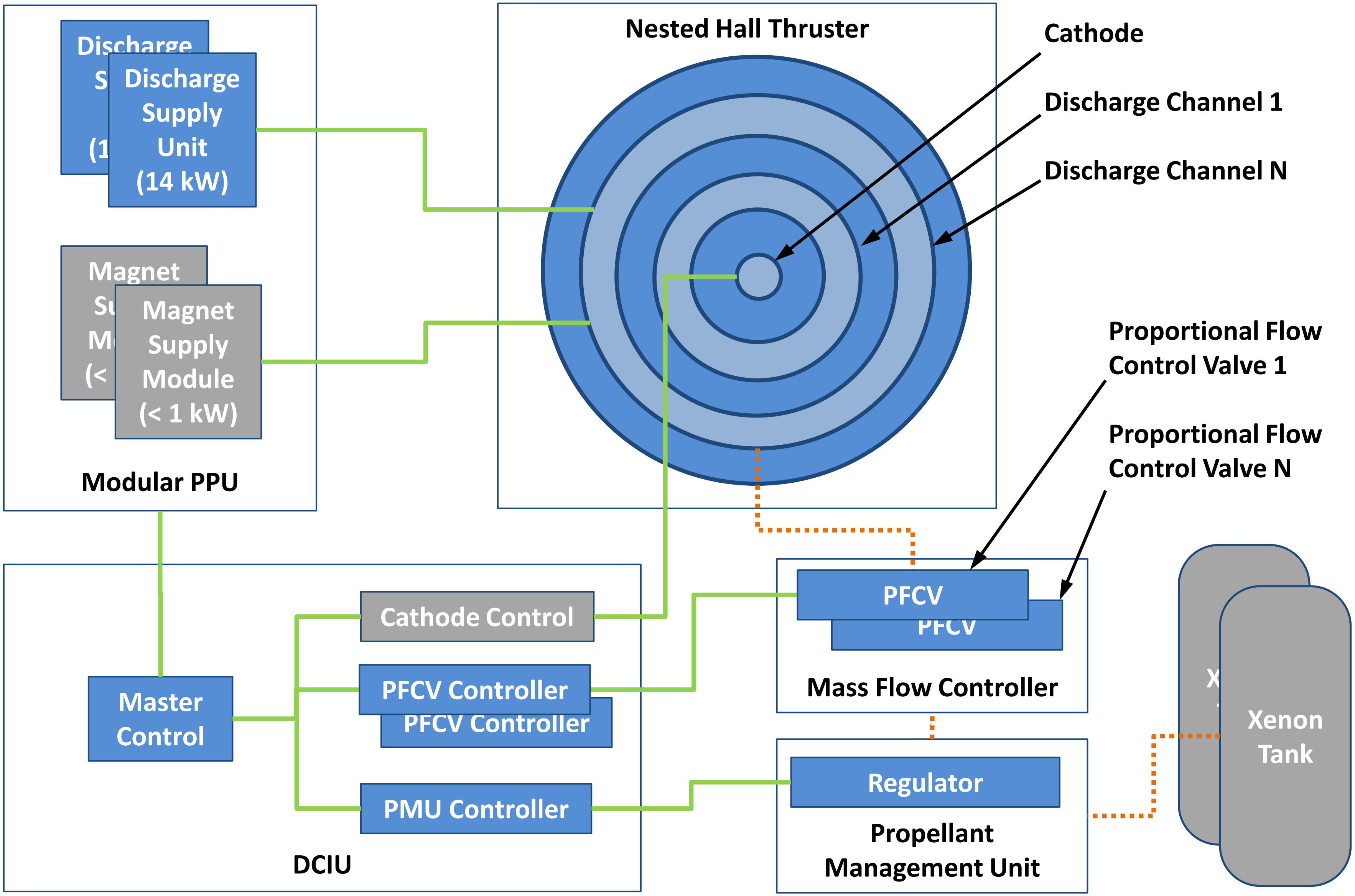
- Next Space Technologies for Exploration Partnerships
- Objectives: Advance the TRL of high power Electric Propulsion systems
  - 50 kW to 300 kW per thruster range
  - Test at a minimum system input power of 100 kW for 100 hours
  - Scalable to MW
  - Extended lifetime and operational (thrusting) time
- 36 month effort with potential follow-on efforts for further maturation

2018 Program Requirements	TRL 5 demonstration power	100 kW
	TRL 5 steady state operation time	100 h
Long Term Objectives	Specific Impulse	~2,000 to ~5,000 s
	In-space lifetime capability	>50,000 h
	Operational lifetime capability	>10,000 h
	System efficiency	>60%
	Power per thruster	100 kW
	System kg/kW	<5 kg/kW

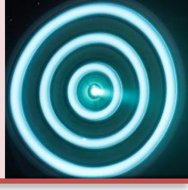
BLOCK DIAGRAM OF XR-100



Blue blocks under development as part of NextSTEP program

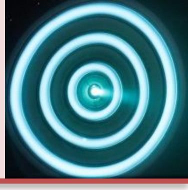


Why XR-100 Nested Hall Thruster?



- System is an evolution of flight-proven Hall thruster technology
- System presents a stable DC electrical load to the spacecraft power system that can be gradually ramped up to avoid large power transients.
- System operates efficiently between 25 kW and 100 kW.
- NHT passively radiates all of the heat generated during operation and requires no active or conductive cooling.
- NHT may be located several meters away from the PPU and XFC.
- NHT has a low volume and compact footprint facilitating spacecraft integration.
- NHT magnetic field is DC and relatively weak outside thruster, allowing installation of other devices within close proximity.
- NHT architecture benefits from ongoing research in high-power Hall thrusters and hollow cathodes performed at multiple institutions across the country (AEPS, etc.)

XR-100 Program Status



2016

- ✓ PPU: Demonstrate stable 10 kW operation using a single discharge supply module operating into resistive loads
- ✓ NHT: Demonstrate stable operation of each discharge channel and characterize thermal behavior
- ✓ MFC: Demonstrate proportional flow control capability of the low-cost valve design
- ✓ MFC & PPU: Demonstrate closed-loop flow control

2017

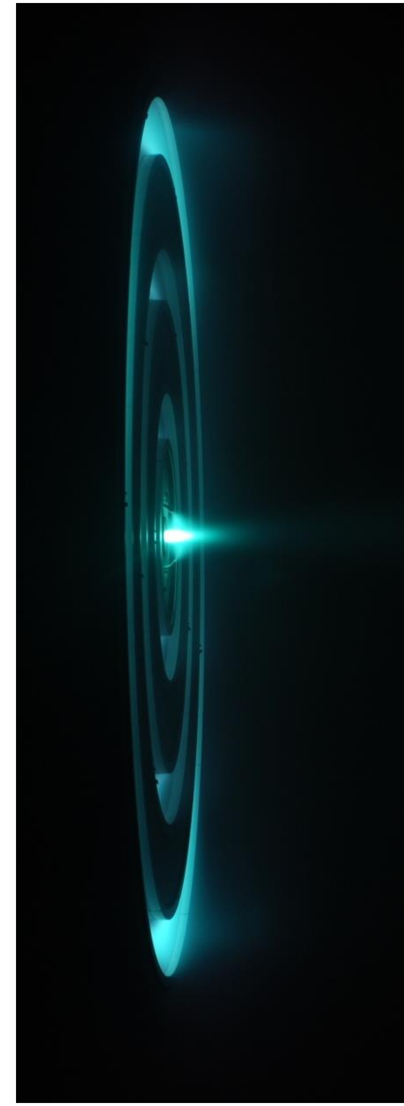
- ✓ NHT: Demonstrate stable operation of 3 discharge channels operating in parallel at 100 kW total input power for 10 min, 80 kW for 2 hours
- ✓ MFC: Demonstrate proportional flow control capability of 5 valves integrated into the MFC manifold
- ✓ System: Demonstrate stable operation in closed-loop control at 10 kW input power

2018

- PPU: Demonstrate ability to support power levels up to 100kW via stable 45kW operation using 3 parallel discharge supply modules operating into resistive loads
- System: Demonstrate stable operation at 100 kW input power for 100 continuous hours.

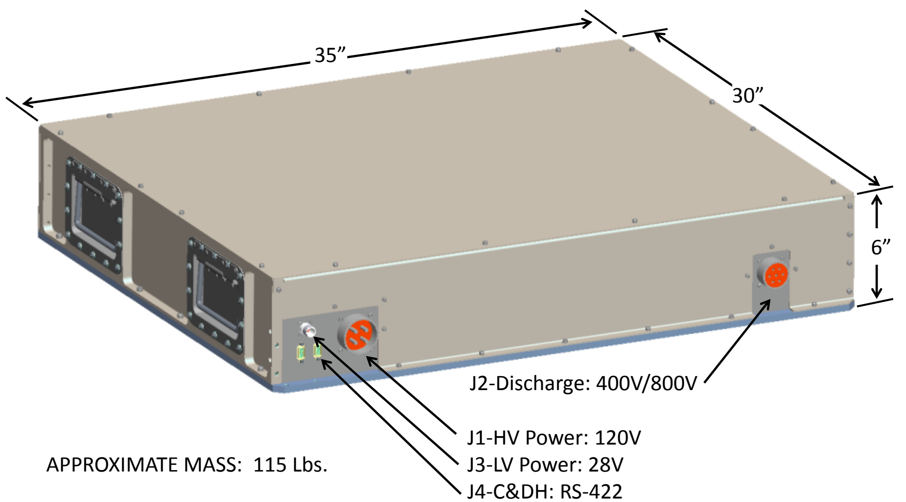
Nested Hall Thruster Design

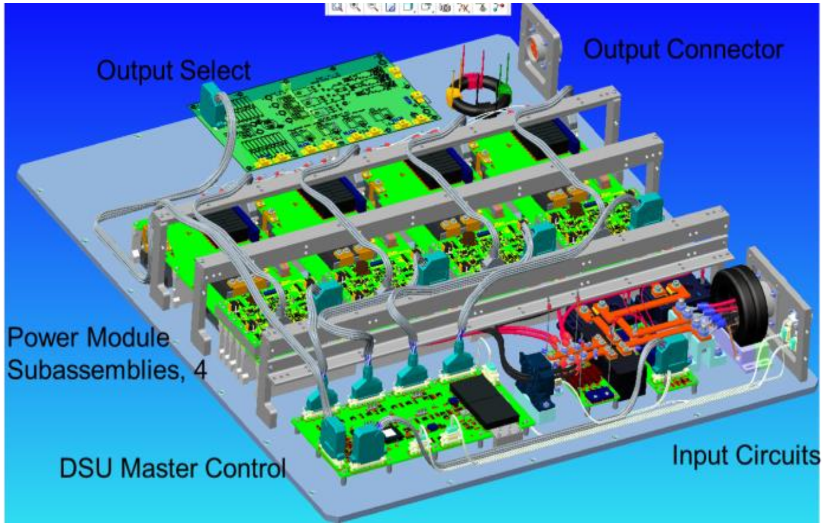
- University of Michigan developed the three-channel X3 NHT in collaboration with the Air Force Research Laboratory (AFRL), NASA GRC, and NASA JPL.
- X3, like other NHTs scales up in power by adding discharge channels.
- Each channel is independently controllable enabling throttleability in thrust and power.
- X3 design leverages extensive work on prior Hall thrusters.
  - X2 (University of Michigan and AFRL), H6 (JPL, AFRL and University of Michigan) , NASA-457M, NASA-400M and NASA-300M
- X3 incorporates a 300A, Lanthanum Hexaboride (LaB6) hollow cathode developed by JPL
- X3 is ~1 meter in diameter and ~10 cm deep
- X3 weighs about 250 kg and was designed to process 200kW yielding a potential specific power of 1.25kg/kW for the thruster.
- 2017 testing at GRC exposed minor design issue due to thermal expansion issue. A design resolution is in place.



Discharge Supply Unit Design

- Consists of Discharge Master Controller, Input Filter, Output Filter and 4 Power Modules
- Each DSU is capable of delivering 13.8 kW
  - At 350V – 400V for maximum thrust
  - At 700V – 800V for maximum Isp

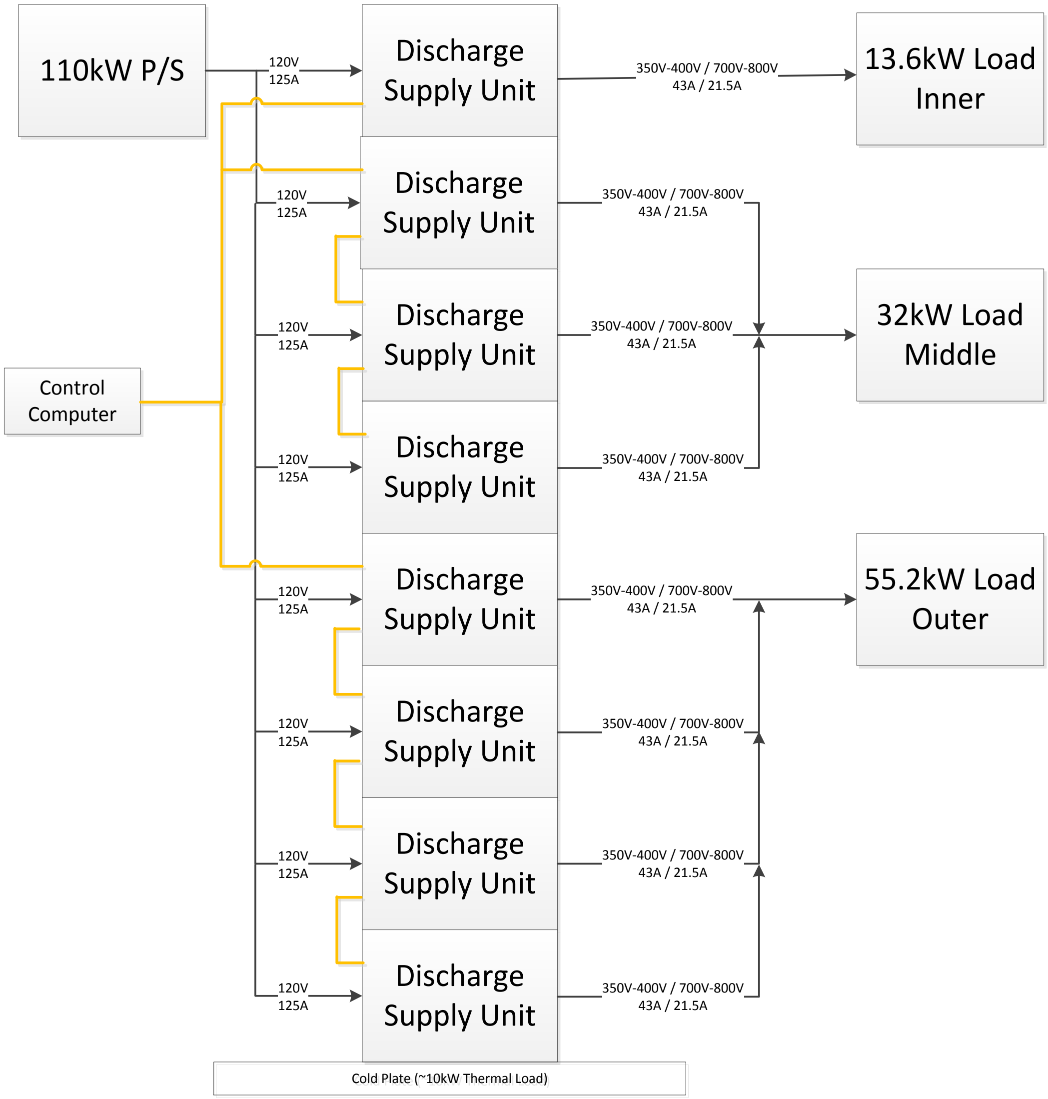




Discharge Supply Unit Assembly

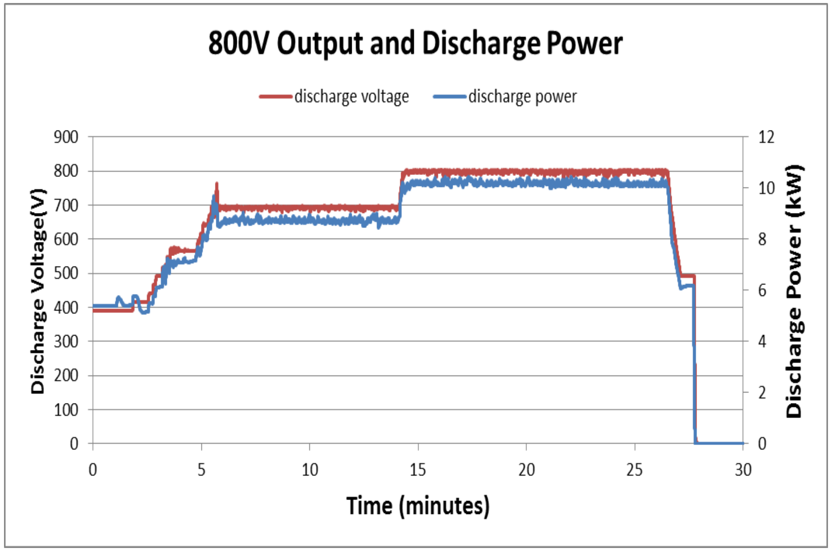
POWER PROCESSOR DESIGN

- Supply provides independent power to each of the 3 discharge channels
- Modular design supports parallel configurations
- Easily expandable to higher powers
- Operates at input voltages between 95V and 120V



2017 PPU Performance During System Test

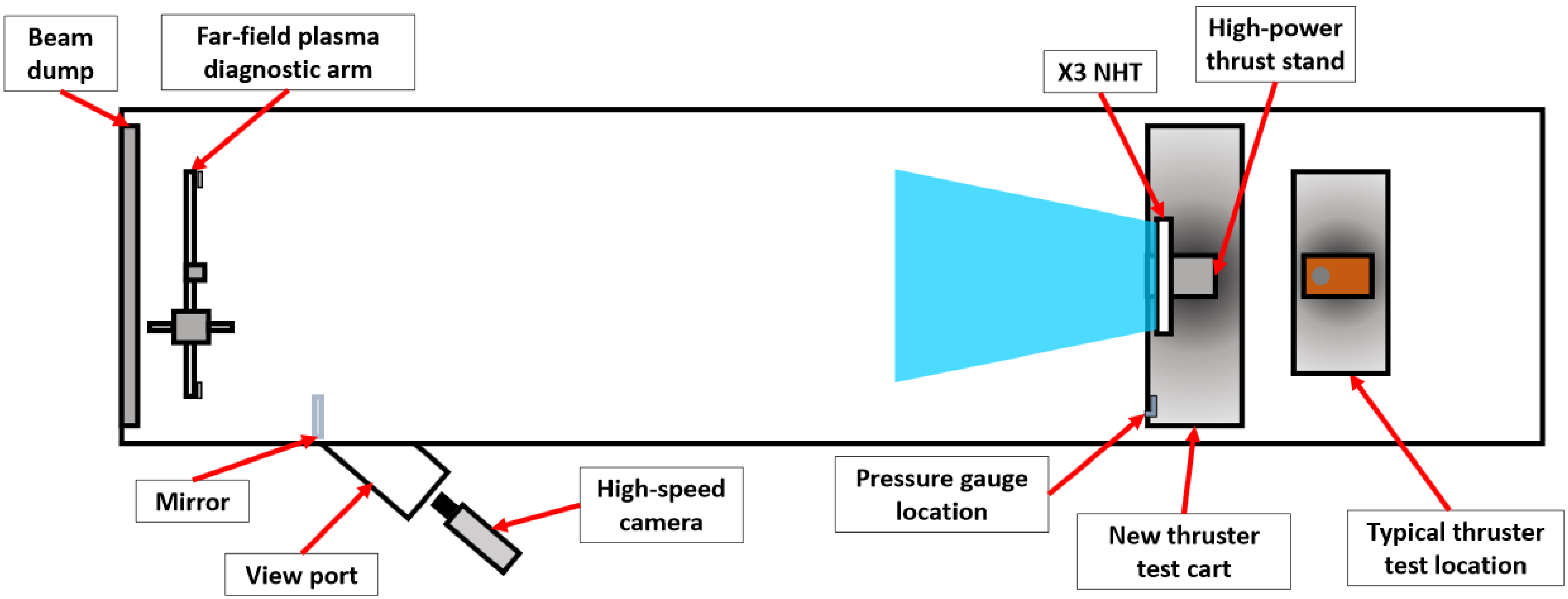
- Testing successfully verified over 10kW operation at output voltages between 400V and 800V.
- Lessons learned from 2016 test were incorporated into the design.
  - Magnetics modified to reduce power losses.
  - Thermal management was improved.
- System demonstrated successful operation during ‘spark events’ showing robust system control



DSU Output at 800V

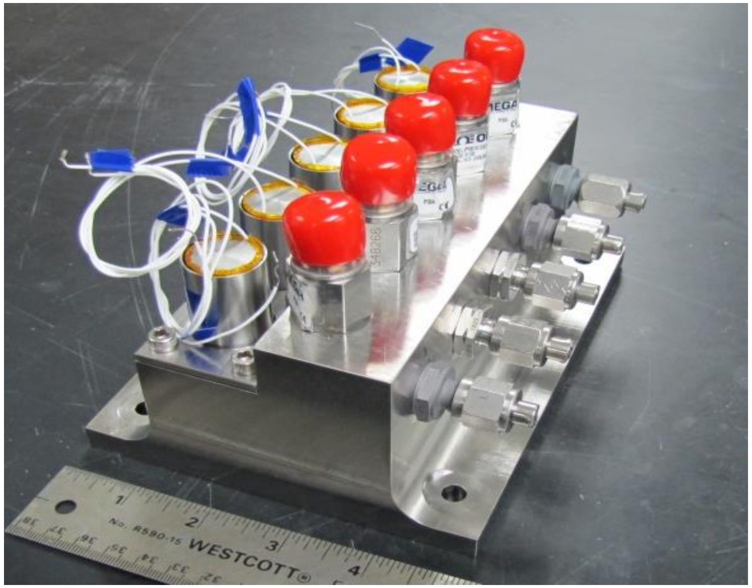
NASA GRC VF5 Test Facility

- NASA GRC VF5 Test Facility planned to support the 100 kW demonstration test



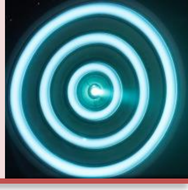
Feed System Design

- NextSTEP program is focused on developing a modular and low-cost components
  - Mass Flow Controller (MFC)
  - Propellant Management Unit (PMU)
- Component are based on Aerojet Rocketdyne proprietary designs
- Both the MFC and PMU use a Proportional Flow Control Valve (PFCV) designed for low cost
  - Wide dimensional tolerances
  - No welding
  - No stroke or load adjustments required
- Prototype unit tested as part of 10 kW demonstration test
- Prototype unit being re-sized to support 100kW demonstration test for 2018

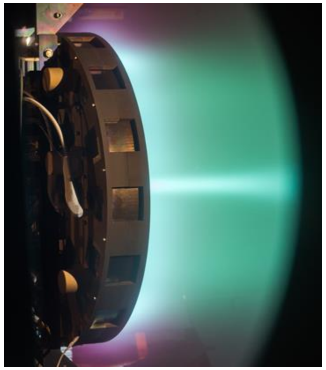


Prototype 5-Valve Mass Flow Controller

NEXTSTEP SUMMARY

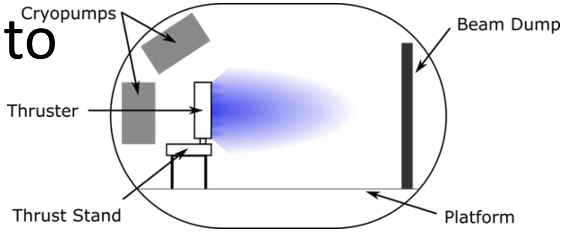


- The XR-100 NHT system is being developed to operate at over 100kW of input power



- A Modular PPU System is being develop to support 100kW EP System

- Multi-Channel Flow Control Value has been develop to support the mass flow required to achieved thrust objective



- 2018 Testing will Demonstrate TRL-5

THE NEXTSTEP AR/MICHIGAN/JPL/GRC TEAM IS DEVELOPING A SCALABLE EP SYSTEM THAT WILL BE CAPABLE WELL OVER 100KW

Acknowledgments

The AEPS / NextSTEP program team would like to thank NASA for their continued support of the work discussed in this paper and all the reviewers, technical consultants and team members at Aerojet Rocketdyne and NASA who have contributed to the success of the program to date.

Portions of the research described in this paper were carried out at the NASA Jet Propulsion Laboratory, under a contract with the National Aeronautics and Space Administration